Whistler-mode Chorus Waves observed on the Cluster spacecraft in the Earth radiation belts

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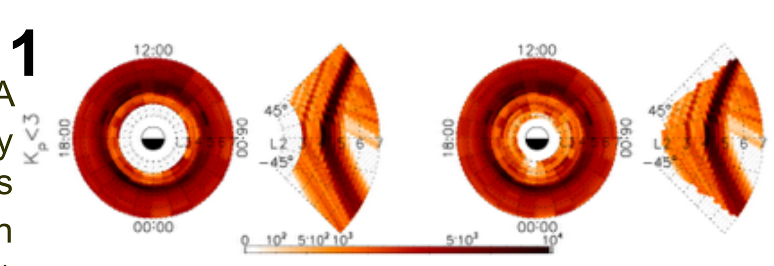
Abstract

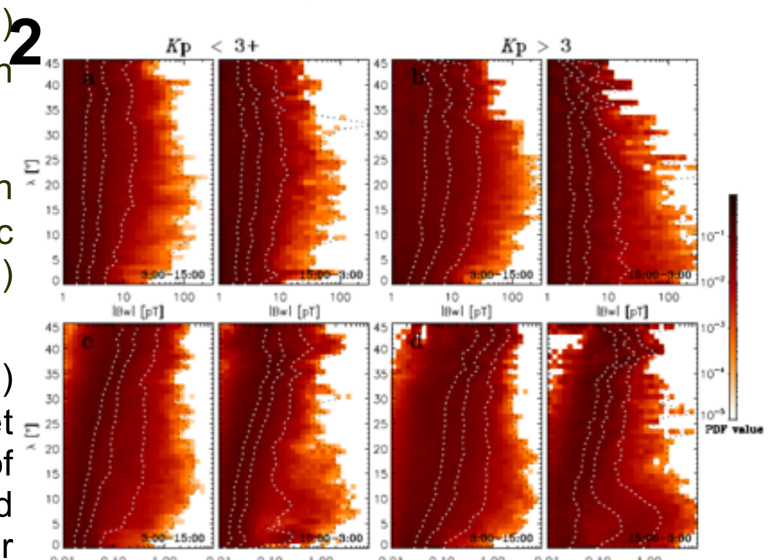
VLF waves play a crucial role in the dynamics of radiation belts, and are responsible for the loss and the acceleration of energetic electrons. Modeling wave-particle interactions requires the best possible knowledge of wave energy and wave-normal directions in L-shells for different magnetic latitudes and magnetic activity conditions. In this work, we performed a statistical study for VLF emissions using a whistler frequency range for ten years (2001-2010) of Cluster measurements. We utilized the data from the STAFF-SA experiment, which spans the frequency range from 8.8 Hz to 3.56 kHz. We present distributions of wave magnetic and electric field amplitude and wave-normal directions dependences upon magnetic latitude, magnetic local time, L-shell and geomagnetic activity in a form of probability levels, which can be directly applied for diffusion coefficients calculation. We show that wave-normals are directed approximately along the magnetic field (with the mean value about 10-15 degrees) in the vicinity of the geomagnetic equator. The distribution changes with magnetic latitude, the angle for a given frequency tends to the resonance cone and as a result at latitudes about 30 degrees, wave-normals become nearly perpendicular to the magnetic field. The observed angular distribution is significantly different from Gaussian and the width of the distribution increases with latitude. Our results confirm earlier analysis of the strong dependence of wave amplitude on geomagnetic activity. An important new finding is the strong dependence of the wave normal direction and wave amplitude on the geomagnetic latitude. Due to this transition of propagation properties of the wave mode, wave electric field increases with latitude and has a maximum near 20 degrees. Wave magnetic field amplitude has minimum at the magnetic equator but increases rapidly with latitude, and has its maximum near 12-15 degrees.

Data set and analysis technique

In this study we use a large dataset of VLF waves observed by Cluster between January 2001 and August 2009 inside the equatorial radiation belts region. This region is thought to be of the primary importance for generation of the chorus waves. The Cluster dataset provides a good coverage in MLT and in L-shells shown in Figure 1, where the dependence on magnetic local/L-shell time and the magnetic latitude/L-shell are presented. Magnetic coordinates of the spacecraft have been obtained from the Cluster Predicted Magnetic Position catalogues. Our analysis is primarily based on data from the Spatio-Temporal Analysis of Field Fluctuations – Spectrum Analyzer (STAFF-SA) experiment [*Cornilleau-Wehrlin et al.*, 2003], which calculates the complete spectral matrix (real and imaginary part) of the three magnetic components measured by the STAFF search coil magnetometer and the two electric field components from the EFW experiment [*Gustafsson et al.,* 2001]. The spectral martix is computed on-board for 27 frequency channels which are logarithmically spaced between 8.8 Hz and 3.56 kHz. The analyzed wave frequency range includes electron whistler waves from the lower-hybrid frequency f_{LH} up to the fce. This range is known to be dominated by the plasmaspheric hiss (from f_{LH}) to about 0.1fce), the lower-band chorus (0.1<f/fce<0.5), and the upper-band chorus waves (0.5<f/fce<1), but it excludes the magnetosonic waves and lower-hybrid waves which also can affect the diffusion process. The local values of fce are obtained from the measurements of the FGM flux-gate magnetometers [*Balogh et al.*, 2001].

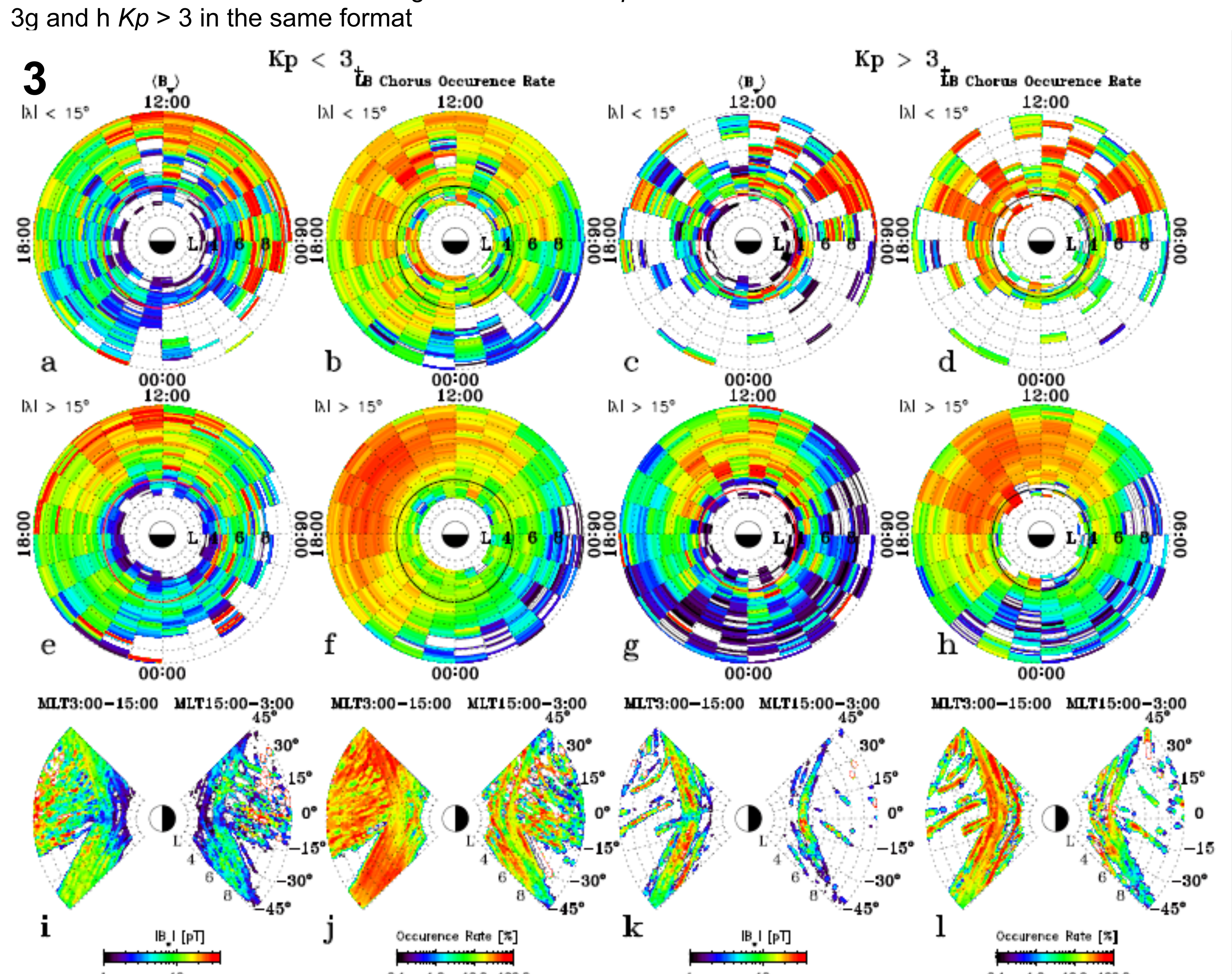


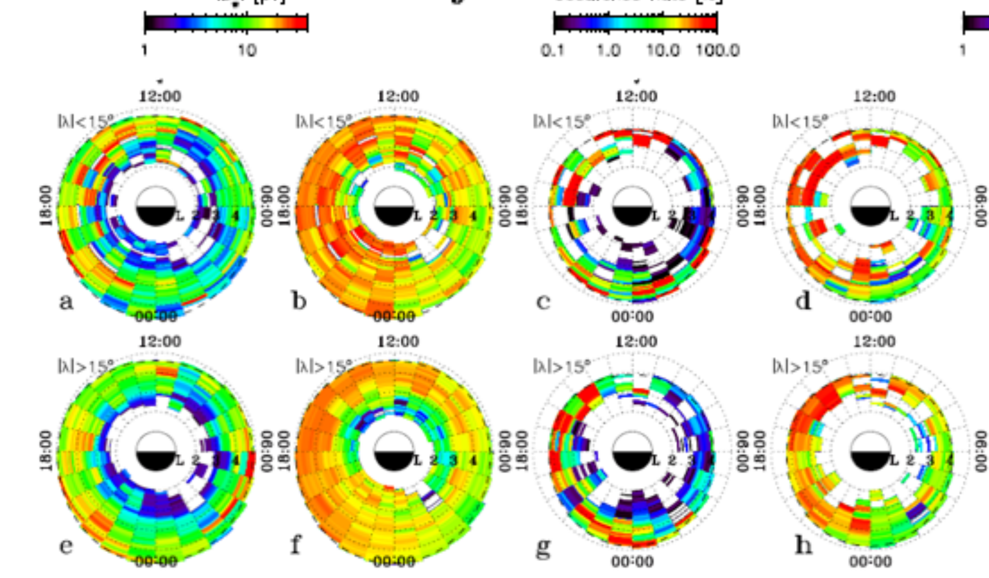
1. Data coverage for the CLUSTER STAFF-SA measurements during 2001--2010 for the chorus frequency range (0.1 f_{ce}< f < 1.0 f_{ce}) in the left panels and for the hiss frequency range (0.02 f_{ce} < f <0.1 f_{ce}) in the right panels and in depends on *L*-shell, MLat and MLT for periods of low (K_p < 3) in the bottom panels, intermediate (3≤K_p≤5), and high geomagnetic activity (K_p > 5) in the top panels.



2. The distribution of the lower band chorus amplitudes in depends on the magnetic latitude : for different geomagnetic activity levels: low (Kp<3), medium (3≤Kp≤5) and hight (Kp>5) respectively.

3. (a) Equatorial chorus averaged wave intensity and (b) occurrence rate shown in *L*-shell/MLT frame for quiet geomagnetic conditions (*Kp* 3). (c and d) Distributions of averaged intensity and occurrence rate for disturbed conditions (*Kp* > 3) are shown, respectively. Distributions for midlatitude chorus are shown in Figures 3e and 3f *Kp* 3 and 3g and h *Kp* > 3 in the same format

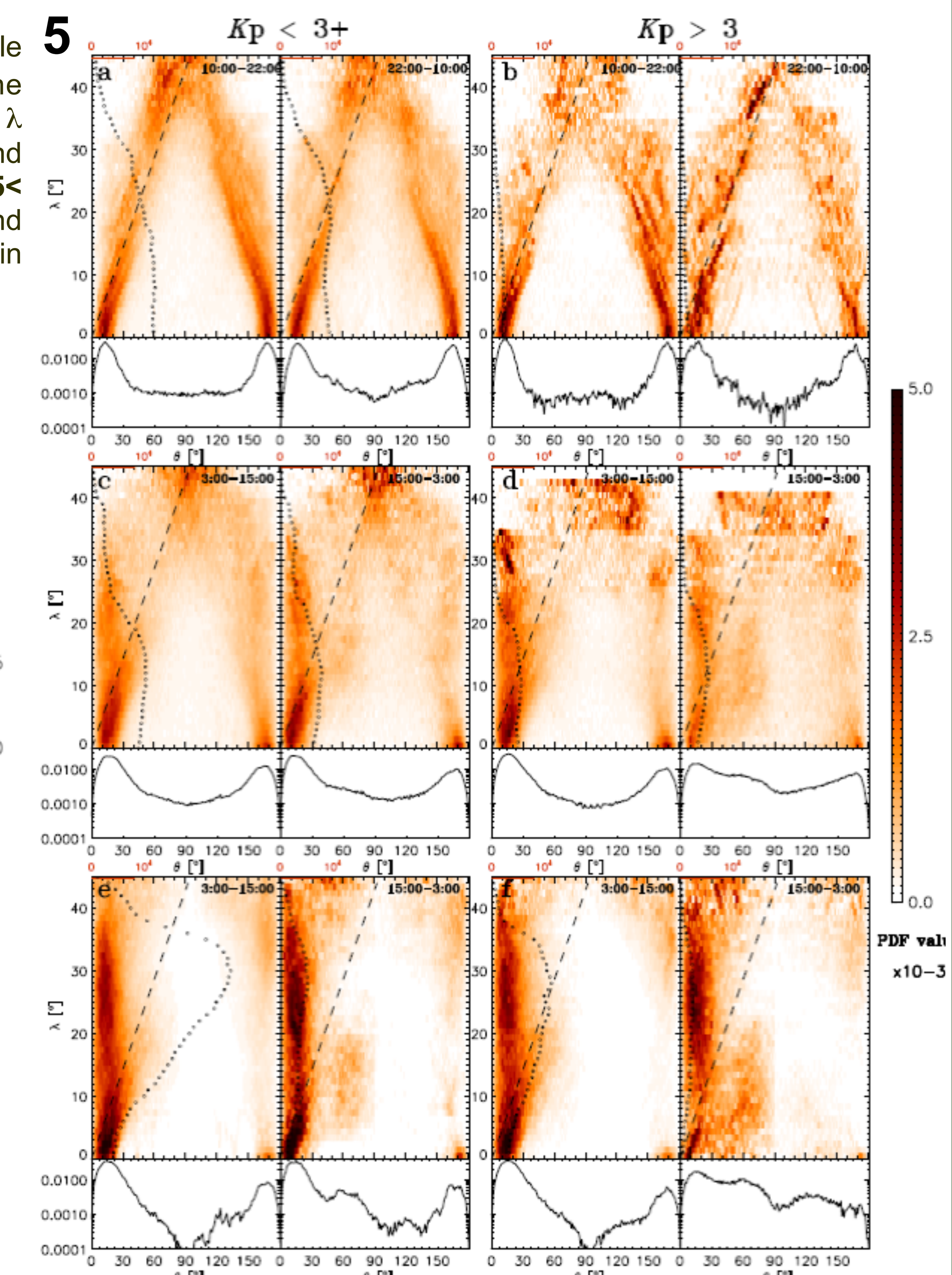


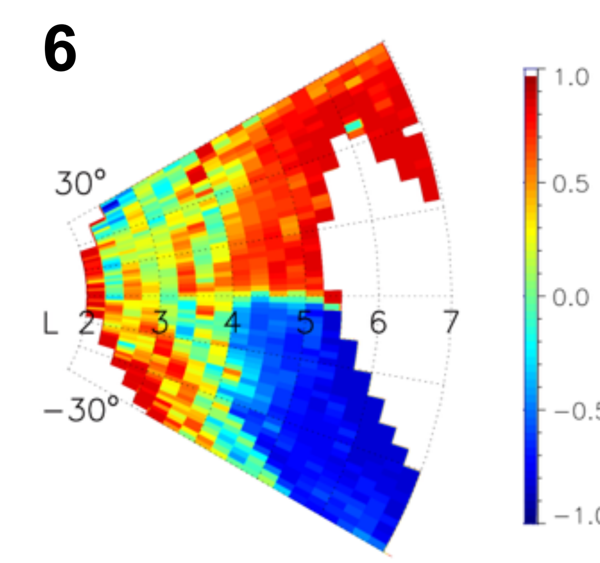


3. . (a) Equatorial hiss averaged wave intensity and (b) occurrence rate shown in *L*-shell/MLT frame for quiet geomagnetic conditions (*Kp* <3). (c and d) Distributions of averaged intensity and occurrence rate for disturbed conditions (*Kp* > 3) are shown, respectively. Distributions for midlatitude hiss are shown in Figures 4e and 4f *Kp*< 3 and 3g and h *Kp* > 3 in the same format

Angular distribution of the whistler wave-vector direction

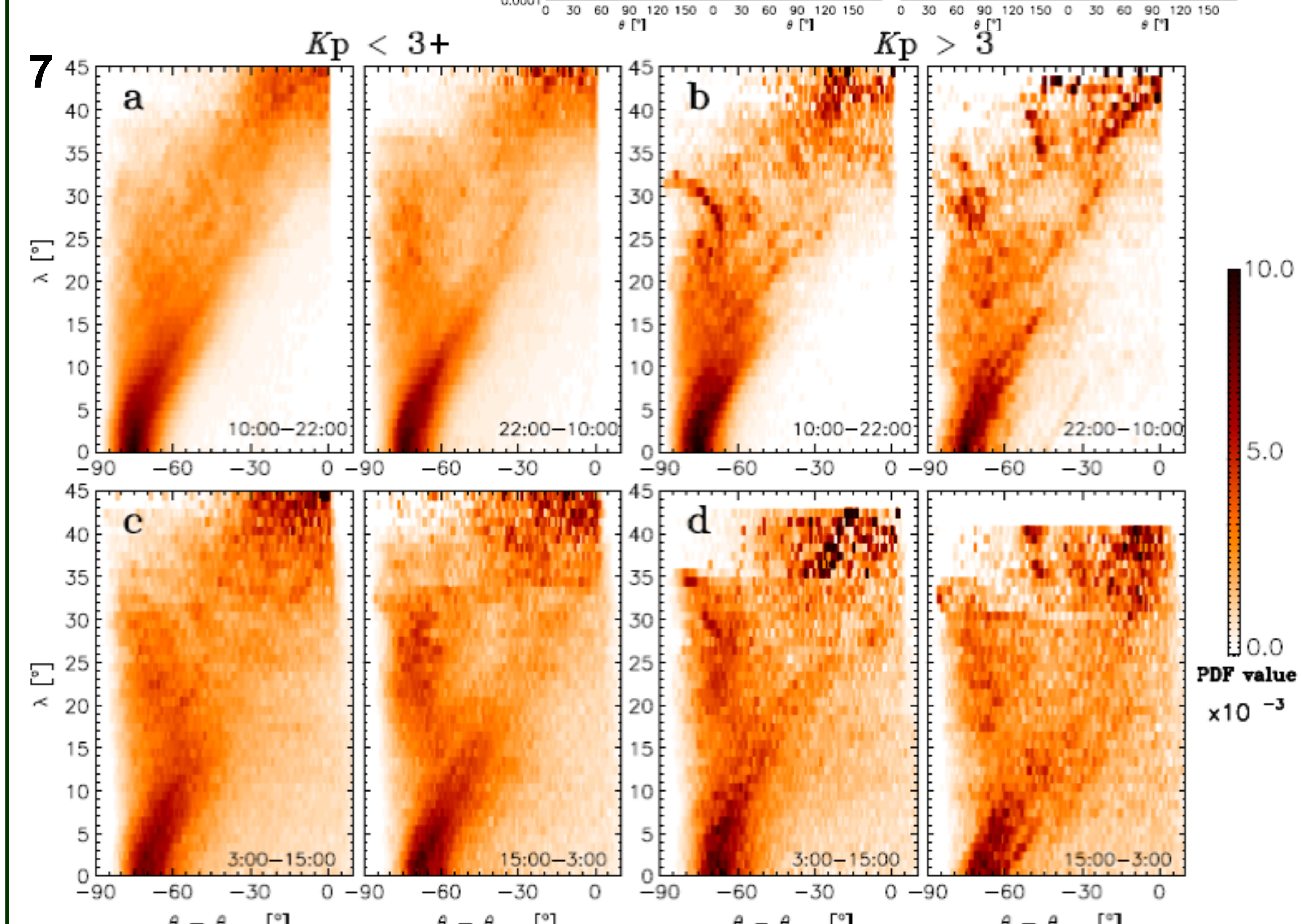
5. The distribution of θ - the angle between the wave-vectors and the background magnetic field for different λ (4<*L*<7) for hiss(panels **a** and **b**) and chorus (panels **c**,**d - 4<L<5.5, e,f – 5.5< L<7**) waves frequency ranges. Day and night sectors are shown in the left and in the right figures of each panels.

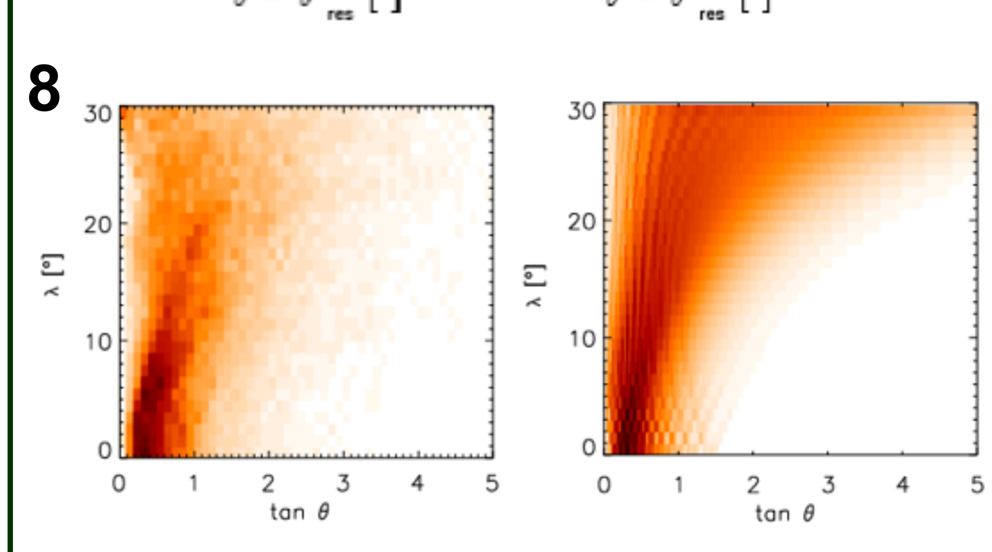




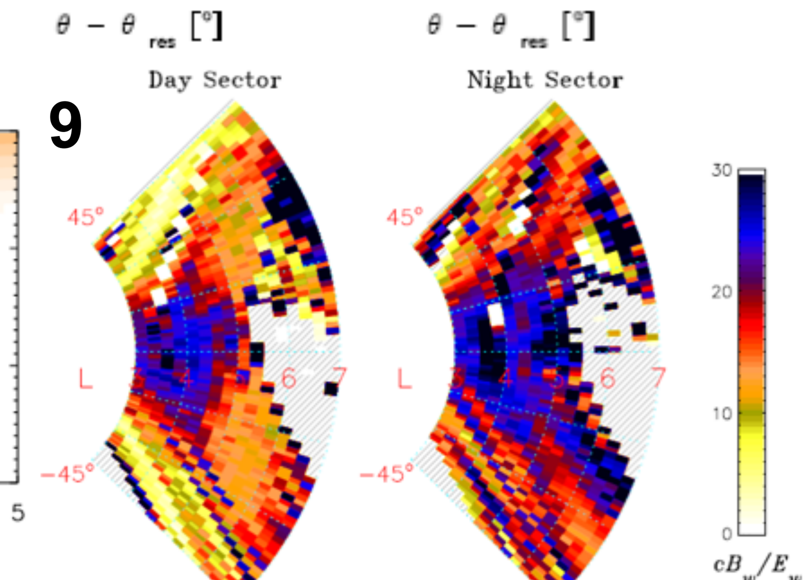
6. The dominant direction of the Poynting flux for chorus and hiss

7. Difference between —the angle between the wave vector and the background magnetic field—and θ_{res}. An approximate value was used θ_{res}= arccos(*f/fce*) (4 < *L* < 5.5) for (a and b) chorus and (c and d) hiss frequency ranges.





8. The PDF of tan θ distribution (X axis) infunction of λ (Y axis) from from CLUSTER experimental data (left panel) and from ray tracing numerical calculation (right panel).



9. The ratio c|Bw|/|Ew| in λ– *L*-shell frame. The median values of c|*Bw*|/|*Ew*| PDF (the channel with the central frequency equal to 1760 Hz) are shown for (left) day and (right) night sectors

Conclusions

We have obtained a statistical distribution for wave-normal directions as a function of λ. The distribution of θ(the angle between the wave-vector and the background magnetic field) at the geomagnetic equator was concentrated in a 30° cone, with a maximum around 15°-20°. Our results are similar to results based on measurements in the vicinity of the geomagnetic equator as presented by [*Burton and Holzer*, 1974, *Hayakawa et al.*, 1984, *Agapitov et al.*, 2010, *Li et al.,* 2011], and [*Agapitov et al.,* 2011]. With increasing of λ, the distribution spreads toward more oblique to the background magnetic field wave-normals, reaching resonance angles at λ ≈15°-20°, consistent with results obtained by [*Burton and Holzer,* 1974] and [*Muto et al.,* 1987] for the lower band chorus, by [*Haque et al.*, 2010] for the upper band chorus, and by [*Hayakawa et al.*, 1986] for hiss. The probability density functions of wave amplitudes and wave-normals are usually non-symmetric and has significant non-Gaussian tails. Therefore, one can suggest that they cannot be well-described by averaged amplitude values. Wave-normals tend to the resonance cone, thus waves propagate in a quasi-electrostatic mode till their reflection λ ≈ 25°-35° for hiss and λ ≈ 45-55° and lower-band chorus respectively.

Acknowledgements: The research was performed under PROGRESS project funded from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637302